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COMPLEX RELATIVE PERMITTIVITY EXTRACTION TECHNIQUE OF BIOTECHNOLOGY MATERIALS IN MICROWAVES DOMAIN

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ABSTRACT

We have established a test fixture and procedure to extract dielectric complex permittivity for biotechnology materials, especially those used in medical (human tissue and liquid 900MHz), environmental domains (i. e., raffia palm trees, spring water) and food (semolina and polenta) in microwave domains. Two circular coaxial transmission-lines have been designed, manufactured and presented in this paper to reach main goals. The technique is based on the use of the transmission-line propagation constant. This technique is broadband, easy to implement and no need to use the form-factor during the computational procedure. The test-designed fixture has made to ease its filling with sample to characterize. The use of the wave cascade matrix to solve discontinuity effects is applied through two different transmission line lengths with identical geometries. That's the way we solved discontinuities and pointed out mathematical formula limits. This apparatus offers the equipotentiality of the electric field and can be used to measure liquid, mud, gunpowder and granulate materials, but it needs buffering wafer samples. All samples used in this apparatus are supposed non-magnetic, and our study has been approved only when the Quasi TEM-mode is propagated.

KEYWORDS: Dielectric Constant, Transmission-Line, Discontinuity, Biotechnology & Characterization

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Original Article

1. INTRODUCTION

Thebroadband technique suggested in this paper is a way to measure S-parameters and extract liquid (spring water, human tissue and sound-conducting gel), sand, food (semolina and polenta) materials along with palm tree (vinifera and laurentiis varieties) complex relative permittivity from a circular coaxial transmission-line fixture. Those materials findtheir applications in medical, environmental and other industrial contexts. Several alternative techniques have been explored in the extant literature [1]–[8], but what we present points out the possibility of using biotechnology materials (medical, sand, food and palm trees) through stringent mathematic formulation impactswithout the use of the form-factor. This is a quick and easy technique when the fixture is completely full of the sample under test (SUT). The technique limits is caused by the propagation of high order modes [9]-[10]. The transmission-line technique is suitable for a large frequency range, but discontinuities at connectors and test cell interfaces limit its use. In those latter cases, the use of two transmission-lines is a good way to sort it out instead of choosing an equivalent electric circuit representing those discontinuities. Both lines are differentiated by their lengths, but the diameters and cell geometry (circular in this case) are the same. The measurement of S-parameters constitutes the fundamental basis of this technique along with the wave cascade matrix [C] principle. Therefore, the utilization of the propagation constant γ is a necessity in this technique [6]–[7]. Mathematical formulations require particular attention before being applied. Sometimes, error coefficients get in without their having been detected.

The material under test is trapped inside the fixture to disturb the fields involved. The fixture design employed an O-ring to avoid the spreading of liquid and/or the creation of intra-fixture bubbles. We describe the technique with more details and rock it through some experimental results: liquid 900 MHz, human tissue, spring water, semolina, polenta, aquarium sand and two raffia palm tree species (vinifera and laurentiis).

2. THEORY AND MATHEMATICAL MODEL

2.1 Propagation Constant

The propagation constant γ is the unique parameter we can extract and must use in this technique. In that case, two different lines, having the same dimensions (inner and outer diameters) but different lengths are used as shown in Figure 1.

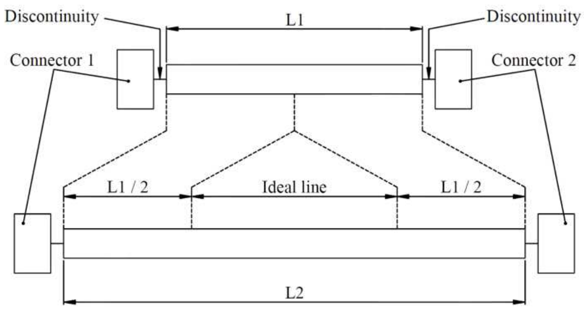

Figure 1: Simplified Representation of Two Transmission-Lines

We suppose the discontinuities to be exactly the same in both interfaces. In such circumstances, any transmission-line measurements can be expressed as:

$$[C] = \begin{bmatrix} e^{\gamma_0 l_0} & 0 \\ 0 & e^{-\gamma_0 l_0} \end{bmatrix} .B. \begin{bmatrix} e^{\gamma_1 l_1} & 0 \\ 0 & e^{-\gamma_1 l_1} \end{bmatrix} .B^{-1}. \begin{bmatrix} e^{\gamma_0 l_0} & 0 \\ 0 & e^{-\gamma_0 l_0} \end{bmatrix} \tag{1}$$

Where,

$$[B] = \frac{1}{1-\Gamma} \begin{bmatrix} 1 & \Gamma \\ \Gamma & 1 \end{bmatrix} \tag{2}$$

And

$$\gamma_k = \alpha_k + j\beta_k \tag{3}$$

Where, l and γ are respectively the length, and the propagation constant ($k = 0$ for connectors and $k = 1$ for the test fixture) α and β are the attenuation and the phase constants, respectively. Γ is the reflection coefficient at the junction interface between connectors and the ideal transmission-line cell. The reflection coefficient Γ is calculated as:

$$\Gamma = \frac{Z_c - Z_0}{Z_c + Z_0} \tag{4}$$

Where, Z_0 and Z_c are respectively the connectors and the transmission-line characteristic impedance. From the scattering matrix $C$of both lines, we directly extract parameters of an ideal transmission line.

$$[C] = \frac{1}{S_{21}} \cdot \begin{bmatrix} 1 & -S_{22} \\ S_{11} & (S_{21}S_{11} - S_{11}S_{22}) \end{bmatrix} \tag{5}$$

Let us use *"i"* and *"j"* to express the line number and consider that X represents imperfections at input and output, together with connectors. We assume that X is unchanged for each transmission-line.

$$[C] = [X] \cdot \begin{bmatrix} e^{\gamma l} & 0 \\ 0 & e^{-\gamma l} \end{bmatrix} \cdot [X] \tag{6}$$

We consider $[C^i] = \begin{bmatrix} e^{\gamma l_i} & 0 \\ 0 & e^{-\gamma l_i} \end{bmatrix}$ and $[C^j] = \begin{bmatrix} e^{\gamma l_j} & 0 \\ 0 & e^{-\gamma l_j} \end{bmatrix}$ are cascade matrices of an ideal transmission line *i* and *j*. The measure matrices of two transmission-lines *i* and *j* of different lengths can be combined into an eigenvalues equation [7]:

$$[C^{ij}] = [C^j][C^i]^{-1} \tag{7}$$

The two eigenvalues can be expressed as:

$$\lambda_{1C,2C} = \frac{\left(C_{11}^{ij} + C_{22}^{ij}\right) \pm \sqrt{\left(C_{11}^{ij} - C_{22}^{ij}\right) + 4C_{21}^{ij}C_{12}^{ij}}}{2} \tag{8}$$

$$\lambda_{1C,2C} = e^{\pm\gamma(L_j - L_i)} \tag{9}$$

It is possible also to write the average of both eigenvalues as:

$$\lambda_{3T} = \frac{C_{11}^{ij} + C_{22}^{ij}}{2} \tag{10}$$

We combine (8), (9) and (10) to solve the propagation constant expression as written below:

$$\gamma = \frac{\ln(\lambda_{1C})}{L_j - L_i} = -\frac{\ln(\lambda_{2C})}{L_j - L_i} = \cosh^{-1}(\lambda_{3C}) \tag{11}$$

The propagation constant is a complex parameter which has real and imaginary parts as written in (3). Then for each configuration, we have equations (12) and (13) wich describe the measurement principle as:

$$\gamma_{vac}(\omega) = \alpha_0(\omega) + j\beta_0(\omega) \tag{12}$$

$$\gamma_{meas}(\omega) = \alpha_g(\omega) + j\beta_d(\omega) \tag{13}$$

$$\alpha_d(\omega) = \alpha_g(\omega) - \alpha_0(\omega) \tag{14}$$

We must measure each line in absence and in presence of sample under test. In formulas (12) and (13), α_0 is the vacuum attenuation factor, α_d the dielectric attenuation factor and α_g is the global attenuation factor. β_0 and β_d are the phase factors of the ideal line, fills up of vacuum and/or sample under test, respectively.

2.2 Relative Complex Permittivity

The structure we designed and manufactured is a circular coaxial fixture. As such, the extracted complex effective permittivity ε_{eff} is determined through the following equation:

$$\tilde{\varepsilon}_{eff} = \left(\frac{\gamma_{meas} - \alpha_0}{j\beta_0}\right)^2 = \left(\frac{\beta_d}{\beta_0}\right)^2 - \left(\frac{\alpha_d}{\beta_0}\right)^2 - 2\,j\,\frac{\alpha_d\beta_d}{\beta_0^2} \tag{15}$$

The coaxial fixture is homogeneous, and to determine the material complex relative permittivity, we have to consider the following: $\tilde{\varepsilon}_r = \tilde{\varepsilon}_{eff}$. The relative permittivity is given as a complex parameter:

$$\tilde{\varepsilon}_r = \varepsilon_r' - j\varepsilon_r'' \tag{16}$$

From (15) and (16), we deduct the material relative permittivity with an error coefficient as:

$$\varepsilon_r' \pm \Delta\varepsilon_r = \left(\frac{\beta_d}{\beta_0}\right)^2 - \left(\frac{\alpha_d}{\beta_0}\right)^2 \tag{17}$$

and its loss tangent as:

$$\tan\delta_d = \frac{1}{\left[1 - \left(\frac{\alpha_d}{\beta_d}\right)^2\right]} \cdot \left(2\,\frac{\alpha_d}{\beta_d}\right) \tag{18}$$

From electromagnetic principles, when the structure is homogeneous, the material relative permittivity and loss tangent are written as:

$$\varepsilon_r = \left(\frac{\beta_d}{\beta_0}\right)^2 \tag{19a}$$

$$\tan\delta_d^{real} = 2\,\frac{\alpha_d}{\beta_d} \tag{19b}$$

It means that there is an error factor $\Delta\varepsilon_r = \left(\frac{\alpha_d}{\beta_0}\right)^2$ on the relative permittivity and on the loss tangent, according to the material loss level for the last case. Equation (18) says that there is a certain error coefficient:

$$y = \frac{1}{\left[1 - \left(\frac{\alpha_d}{\beta_d}\right)^2\right]}$$

If $\left(\frac{\alpha_d}{\beta_d}\right) << 1$, in that case, $y \approx 1$.

If $\left(\frac{\alpha_d}{\beta_0}\right) \approx 1$, the real loss tangent factor will be get an error which is times “y”.

If we suppose that $x = \left(\frac{\alpha_d}{\beta_d}\right)^2$, the Taylor expansion of the function about zero of orders one is:

$$y = \frac{1}{1-x} = 1 + x$$

Then equation (18) combined to equation (19b) becomes:

$$\tan \delta_d = (1 + x)\tan \delta_d^{real} \quad (20)$$

Using that expression gives an error of:

$$\Delta tan\delta_d = xtan\delta_d^{real}$$

Definitely, there are two main equations to be used when characterizing material: equations (19a) and (19b). If not correcting at each step of the technique implementation, errors on relative permittivity and loss tangent are:

$$\Delta \varepsilon_r = x\varepsilon_r \quad (21a)$$

$$\Delta \tan \delta_d = x \tan \delta_d^{real} \quad (21b)$$

The level of error depends on x; in other words, the level of material losses. Despite the fact that the error on the relative permittivity and the loss tangent is a subtraction and addition for relative permittivity and loss tangent, respectively, according to equation (21), that error is proportional to x with ε_r for relative permittivity and $tan\delta_d^{real}$ for loss tangent.

3. RESULTS AND ANALYSIS

Measurements were performed on a VNA in the frequency range of 500 MHz to 10.5 GHz with some specifications depending on the use of SUT. All S-parameter measurements have been treated through algorithms when using MathCad software. We have presented results when using biological, food and environment materials to validate the principle. In order to demonstrate the relevance of the proposed technique, circular coaxial lines manufactured with brass as conductor have been investigated with the ease of integration of SUT. Inner diameter of the outer conductor is $D = 14.36$mm while the outer diameter of the inner conductor is $d = 4$ mm as it is shown in Figure 2.

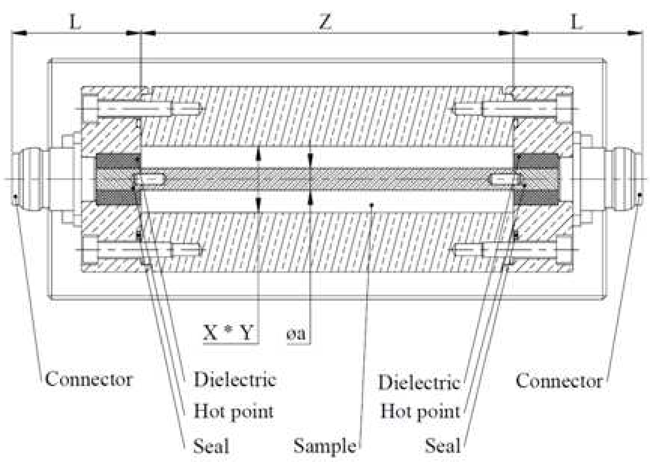

Figure 2: Simplified Representation of the Scan Cell

Scattering parameters have been measured using a 2-port performance Vector Network Analyzer (VNA) MS46522B-Anritsu system in the frequency range 500 MHz – 10.5 GHz with previous calibration.

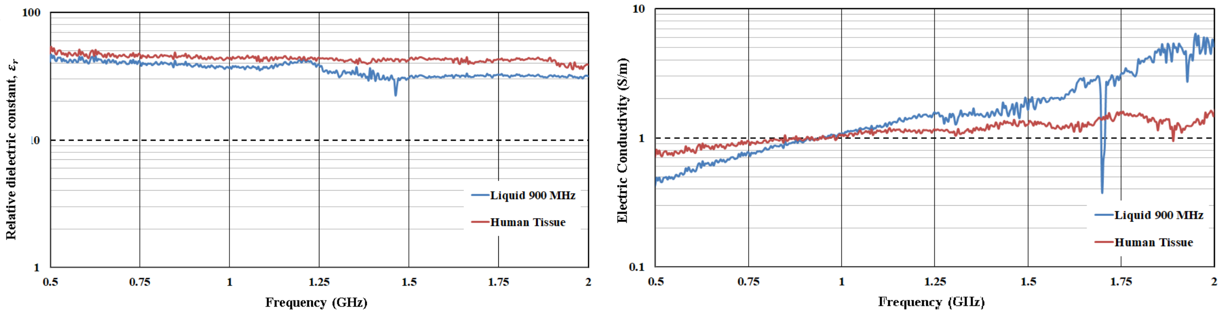

Figure 3: Electric Parameters of Liquid 900 MHz and Human Tissue

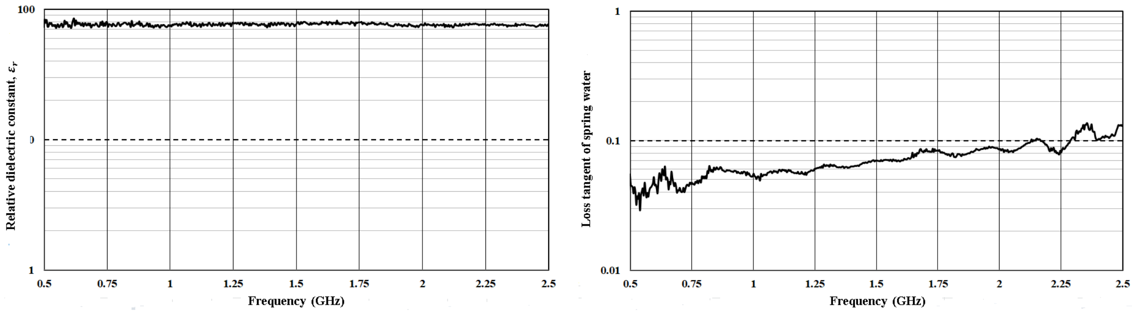

Figure 4: Relative Permittivity and Loss Tangent of Spring Water

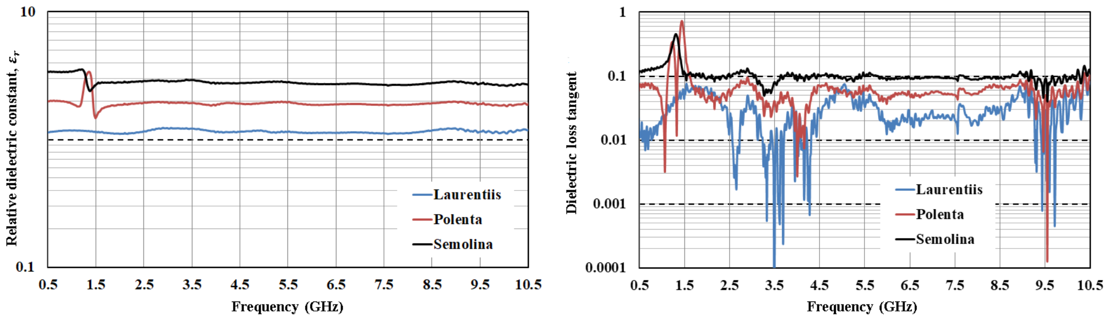

Figure 5: Relative Permittivity and Loss Tangent of Laurentiis, Polenta and Semolina

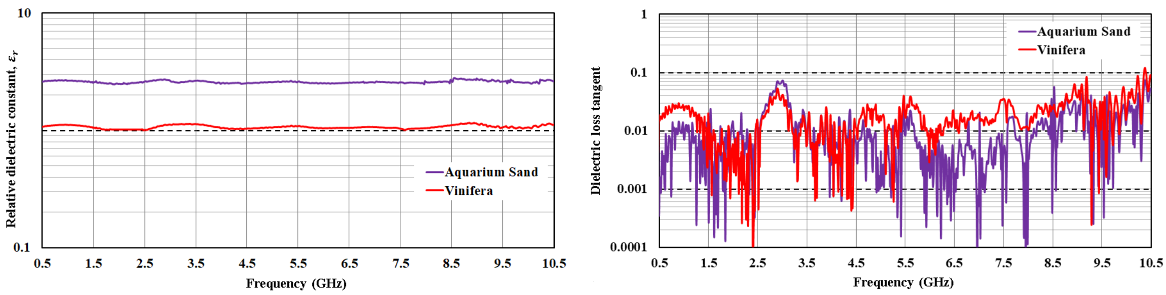

Figure 6: Relative Permittivity and Loss Tangent Aquarium Sand and Vinifera

Compared to the human tissue manufacturer values ($\varepsilon_r = 42.3$ and $\sigma = 1.52$ S/m) obtained at 2 GHz, we got the results with 5.3% and 3.29% of error respectively, which represents $\varepsilon_r^{HT} = 40.065$ and $\sigma^{HT} = 1.47$ S/m. Also, the liquid 900 MHz manufacturer targets have been $\varepsilon_r = 39.3$ and$\sigma = 0.95$ S/m while we measured $\varepsilon_r^{L} = 38.096$ with $\sigma^{L} = 0.945$ S/m corresponding to 3.06% at 900 MHz. We can definitely certify that the way we computed the extraction procedure is

fine up to 4% of error in all parameters.

4. CONCLUSIONS

The transmission-line technique is one of several well-known, commonly used techniques. In this paper, we presented that broadband technique to extract complex permittivity from measured S-parameters. The sample to test fills up the fixture and is trapped through two connectors, allowing for closure of the entire fixture. We proved the impact of ignoring the error coefficients on the relative permittivity and on the loss tangent through mathematical assumption. We have cured mathematic theory through experimental results.

The two transmission-line technique is characterized by its ability to better solve imperfections at each contact interface between the ideal line and the connectors. However, when computing mathematic formulas, it numerically introduces some errors that can easily be solved. Due to the cell dimensions and discontinuities at connector-fixture interfaces, higher modes propagate and generate the phase constant distorting. Linearising that parameter becomes rough and the frequency range study gets limited. In matter of fact, we have proved in this paper, through experimental strengthening that the coaxial fixture is well suited to measure complex permittivity of biotechnology materials.

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